NOV 6 1981

660

I27.2:R31/12

ORIGINAL

RESISTIVITY DATA ANALYSIS OF A MULTILAYERED MEDIUM BY COMPUTER CURVE-MATCHING TECHNIQUES

COMPLETED

40

May 1981

Engineering and Research Center
Bureau of Reclamation
UNITED STATES DEPARTMENT OF THE INTERIOR

MS-230 (3-78)
Water and Power

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Resistivity Data Analysis of a Multilayered Medium By Computer Curve-Matching Techniques		5. REPORT DATE May 1981 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ulrich Schimschal		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bureau of Reclamation Engineering and Research Center Denver, Colorado 80225		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 13. TYPE OF REPORT AND PERIOD COVERED
12. SPONSORING AGENCY NAME AND ADDRESS Same		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Editor-BDM

16. ABSTRACT

A computer program using a curve-matching technique has been developed to aid in the interpretation of earth surface electrical resistivity data for the case of a multilayered medium. The program accepts apparent resistivities and array spacings obtained exclusively from a Wenner array. The program employs an iterative technique to match field data with computer model data obtained for a distribution of horizontal layers of varying thickness and resistivities. The assumed initial layer distribution can then be modified by the interpreter and the result can be resubmitted for further iterations in order to increase the accuracy of the final curve matching.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- /*earth resistivity (electrical)/ *geological investigations/ engineering geology/ geophysics/ *computer programs/ *curve fitting/ curve matching/ computer models

b. IDENTIFIERS--

c. COSATI Field/Group 08G COWRR: 0807

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 34
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE

GPO 854-612

RESISTIVITY DATA ANALYSIS OF A MULTILAYERED MEDIUM BY COMPUTER CURVE-MATCHING TECHNIQUES

by

Ulrich Schimschal
(now with USGS)

Geophysics Section
Geologic Services Branch
Division of Geology
Engineering and Research Center
Denver, Colorado
May 1981

UNITED STATES DEPARTMENT OF THE INTERIOR Bureau of Reclamation

I

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

In May of 1981, the Secretary of the Interior approved changing the Water and Power Resources back to its former name, the Bureau of Reclamation.

The information contained within this report was developed for the Bureau of Reclamation; no warranty as to the accuracy, usefulness, or completeness is expressed or implied.

BEST DOCUMENT AVAILABLE

CONTENTS

	Page
Introduction	1
Theory	1
Gauss-Legendre Quadrature	8
Description of the program	9
Testing the program	10
Conclusions	14
Bibliography	16
Appendix	17
Program parameters	17
Program listing	20
Example of Option A	29
Example of Option B	30
Example of Option C	31
Example of delayed processing	33

FIGURES

1	Model of horizontally layered earth	1
2	Four-point electrode array	4
3	Wenner array	6
4	Three-layer model using surface spacing for layer thickness approximation at various incremental units of resistivity (Model A, Option B)	11
5	Three-layer model using surface spacing for layer thickness approximation at various incremental units of resistivity (Model B, Option B)	12

INTRODUCTION

Field data obtained from geophysical surface-resistivity measurements cannot readily be interpreted to obtain the true resistivity distribution with depth below the surface. However, for the horizontal-layer earth model, unique interpretations of true resistivity and layer thickness are obtainable. This is accomplished by matching field data obtained over a horizontally layered earth to graphs obtained from a mathematical model. Referring to catalogues of only a minimally useful library of mathematical models can be a vexing task for the interpreter. Hence, it is of obvious advantage to have these graphs generated, matched to the field data, and modified for rematch by a high-speed computer. Should the conditions of a reasonably horizontally layered earth not apply, the computer program developed here will obviously fail. Furthermore, the resistivity of a given layer must be relatively homogeneous throughout.

THEORY

One may approximate a system of horizontally layered sediments by a sequence of horizontal, homogeneous, and isotropic layers extending laterally to infinity and resting on an infinite half-space (see fig. 1).

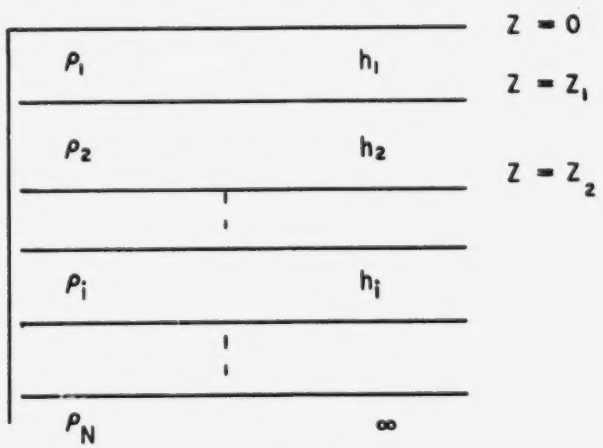

Figure 1.—Model of horizontally layered earth.

For this particular model we make use of the cylindrical coordinate system.

In each one of the layers, the potential U must satisfy Laplace's equation,

$$\nabla^2 U = 0 \tag{1}$$

or, in cylindrical coordinates,

$$\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \frac{\partial^2 U}{\partial z^2} = 0 \tag{2}$$

Separating variables,

$$U(r,z) = R(r)Z(z) \tag{3}$$

leads to the following differential equations:

$$\frac{Z''(z)}{Z(z)} - \lambda^2 = 0 \tag{4a}$$

$$\frac{R''(r)}{R(r)} + \frac{1}{r}\frac{R'(r)}{R(r)} + \lambda^2 = 0 \tag{4b}$$

where λ is an eigenvalue.

Solutions to (4a) are: $e^{-\lambda z}$, $e^{\lambda z}$; and the solutions to (4b) are: $J_0(\lambda r)$ and $Y_0(\lambda r)$. The latter must be discarded out of physical considerations since it tends to infinity for small r. Since a sum of solutions is also a solution, the most general equation is of the form

$$U_i = \int_0^\infty [A_i(\lambda)\, e^{-\lambda z_i} + B_i(\lambda)\, e^{\lambda z_i}]\, J_0(\lambda r)\, d\lambda \tag{5}$$

i.e., one equation for each layer.

The constants $A_i(\lambda)$ and $B_i(\lambda)$ are determined through use of boundary conditions.

BEST DOCUMENT AVAILABLE

We now require that the normal component of current density j_z be continuous across the layer boundaries, except at the surface, where it is equal to zero.

But from Ohm's Laws, we have

$$\bar{j} = \sigma \bar{E} \text{ and } j_{z_i} = -\sigma_i \frac{\partial U_i}{\partial z} \text{ and from (5),}$$

$$\sigma_i \int_0^\infty (-\lambda A_i e^{-\lambda z_i} + \lambda B_i e^{\lambda z_i}) J_0(\lambda r)\, d\lambda = \sigma_{i+1} \int_0^\infty (-\lambda_{i+1} e^{-\lambda z_{i+1}} + \lambda B_{i+1} e^{\lambda z_{i+1}}) J_0(\lambda r)\, d\lambda \quad (6)$$

At the surface, $j_{z_0} = 0$ and $z = 0$

Then

$$\int_0^\infty (-\lambda A_1 + \lambda B_1) J_0(\lambda r)\, d\lambda = 0 \quad (7)$$

which implies $A_1 = B_1 = C$.

This means that for the surface potential the above assumption leads to:

$$U_1 = \int_0^\infty C J_0(\lambda r)\, d\lambda = \frac{2C}{r} \quad (8)$$

From equation (6) it follows that

$$\sigma_i (-A_i(\lambda) e^{-\lambda z_i} + B_i(\lambda) e^{\lambda z_i}) = \sigma_{i+1} (-A_{i+1}(\lambda) e^{\lambda z_i} + B_{i+1}(\lambda) e^{\lambda z_i}) \quad (9)$$

The boundary condition that we have continuity of the potential at the interfaces between layers leads to:

$$A_i(\lambda) e^{-\lambda z_i} + B_i(\lambda) e^{\lambda z_i} = A_{i+1}(\lambda) e^{-\lambda z_i} + B_{i+1}(\lambda) e^{\lambda z_i} \quad (10)$$

Finally, since the last layer $z \to \infty$ the potential must go to zero, requiring $B_N = 0$.

BEST DOCUMENT AVAILABLE

Evaluation of the above results of the boundary conditions leads to an expression for the mutual resistance $Q(r)=\frac{U(r)}{I}$ (where $U(r)$ is the surface potential and I is the current) at the surface of the earth ($z=0$) for the case of N layers (layer N being the infinite half-space) as follows:

$$Q(r)=\frac{\rho_1'}{2\pi}\int_0^\infty K_{N-p}(\lambda)\,J_0(\lambda r)\,d\lambda \tag{11}$$

where the Kernel function $K(\lambda)$ is:

$$K_{N-i}(\lambda)=\frac{1-G_i e^{-2\lambda h_i}}{1+G_i e^{-2\lambda h_i}}$$

and

$$G_i=\frac{\rho_i-\rho_{i+1}K_{N-i-1}}{\rho_i+\rho_{i+1}K_{N-i-1}}$$

and $K_0=1 \quad (i=1, 2, \ldots, N-1)$

Consider next a 4-point electrode array (see fig. 2):

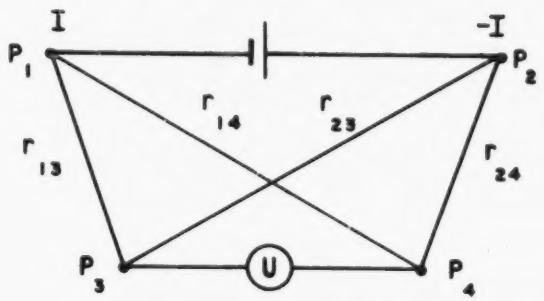

Figure 2.—Four-point electrode array.

BEST DOCUMENT AVAILABLE

We have a current sink at P_2 and a source at P_1. Hence we have to add the potentials due to both. Let $U_{34}^{(+)}$ and $U_{34}^{(-)}$ designate the potentials due to source and sink, respectively, between points 3 and 4:

$$U_{34}^{(+)} = U_3(r_{13}) - U_4(r_{14})$$

$$U_{34}^{(-)} = U_4(r_{24}) - U_3(r_{23})$$

Combining these relationships with the definition of mutual resistance, $Q(r) = \frac{U(r)}{I}$,

we have:

$$U_{34}^{(+)} = +I(Q(r_{13}) - Q(r_{14})) \tag{12a}$$

and

$$U_{34}^{(-)} = -I(Q(r_{23}) - Q(r_{24})) \tag{12b}$$

Adding (12a) and (12b),

$$U_{34} = I[Q(r_{13}) - Q(r_{14}) - Q(r_{23}) + Q(r_{24})] \tag{13}$$

Combining (13) and (11) we have:

$$Q_{34} = \frac{\rho_1}{2\pi}\int_0^\infty K_{N-p}(\lambda)[J_0(\lambda r_{13}) - J_0(\lambda r_{14}) - J_0(\lambda r_{23}) + J_0(\lambda r_{24})]\,d\lambda \tag{14}$$

For a Wenner array (see fig. 3), (14) reduces to:

$$Q_{34} = \frac{\rho_1}{2\pi}\int_0^\infty K_{N-p}(\lambda)[J_0(\lambda a) - J_0(\lambda 2a) - J_0(\lambda 2a) + J_0(\lambda a)]\,d\lambda$$

$$= \frac{\rho_1}{\pi}\int_0^\infty K_{N-p}(\lambda)[J_0(\lambda a) - J_0(2\lambda a)]\,d\lambda \tag{15}$$

BEST DOCUMENT AVAILABLE

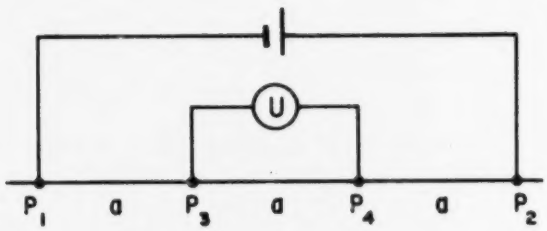

Figure 3.—Wenner array.

The apparent resistivity is defined as $\rho_A = KQ$; where K is the geometric factor. For the Wenner array, $K = 2\pi a$; hence, rewriting (15) we have

$$\rho_A = 2a\rho_1 \int_0^\infty K_{N-p}(\lambda)[J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda \tag{16}$$

The above integral needs to be changed in order to facilitate evaluation on the computer.

We know that the Kernel function eventually goes to unity as λ increases. Let this value of λ be designated as λ_{max}. Thus, we get from (16):

$$\rho_A = 2a\rho_1 \left\{ \int_0^{\lambda_{max}} K_{N-p}(\lambda)[J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda + \int_{\lambda_{max}}^\infty [J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda \right\} \tag{17}$$

However, the second integral can be evaluated as follows:

$$\int_0^\infty [J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda = \int_0^{\lambda_{max}} [J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda + \int_{\lambda_{max}}^\infty [J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda \tag{18a}$$

Also,

$$\int_0^\infty J_0(\lambda a)\, d\lambda - \int_0^\infty J_0(2\lambda a)\, d\lambda = \frac{1}{a} - \frac{1}{2a} \tag{18b}$$

Substituting (18a) and (18b) into (17),

$$\rho_A = 2a\rho_1 \left\{ \frac{1}{2a} + \int_0^{\lambda_{max}} (K_{N-p}(\lambda) - 1)[J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda \right\}$$

BEST DOCUMENT AVAILABLE

or

$$\rho_A = \rho_1 \left\{ 1 + 2a \int_0^{\lambda_{max}} (K_{N-p}(\lambda) - 1)[J_0(\lambda a) - J_0(2\lambda a)]\, d\lambda \right\} \tag{19}$$

Error Computation

Case 1 $f < g$ $f^2 < fg < g^2$

$fg < g^2$

Case 2 $g < f$ $g^2 < fg < f^2$

$fg < f^2$

Error function used:

$$e = 0.5 - \frac{\Sigma f_n g_n}{\Sigma f_n^2 + \Sigma g_n^2}$$

For $f = g$

$$\frac{\Sigma f^2}{2\Sigma f^2} = 0.5$$

and

$$e = 0.5 - 0.5 = 0$$

BEST DOCUMENT AVAILABLE

GAUSS-LEGENDRE QUADRATURE

For the integration the program uses a three-point Gauss quadrature; i.e., a special case of the Gauss-Legendre quadrature technique.

An integral can be approximated in the following form:

$$I = \int_a^b f(x)\,dx$$

$$= (b-a)[R_1\phi(\mu_1) + R_2\phi(\mu_2) + \ldots + R_n\,\phi(\mu_n)] \tag{20}$$

where

$$\phi(\mu_j) = \frac{b-a}{2} f\left[\frac{b-a}{2}\mu_j + \frac{b+a}{2}\right] \tag{21}$$

and the R_n's are known as Gauss coefficients.

For the problem at hand a maximum saving in computer time was experienced when using a three-point quadrature. To obtain equivalent accuracy compared to that of the trapezoidal approach, the computer time required was reduced to about one-fourth.

The function to be integrated is subdivided into increments λ_i, not necessarily equal, and one obtains:

$$\phi_i(\mu) = \frac{\lambda_{i+1}-\lambda_i}{2} f\left(\frac{\lambda_{i+1}-\lambda_i}{2}\mu + \frac{\lambda_{i+1}+\lambda_i}{2}\right) \tag{22}$$

For the three-point quadrature (20) reduces to:

$$I_G = \phi\left(-\frac{1}{\sqrt{3}}\right) + \phi\left(+\frac{1}{\sqrt{3}}\right) \tag{23}$$

requiring an appropriate mapping of our function that is to be integrated.

BEST DOCUMENT AVAILABLE

Then

$$\phi_i(\mu) = \frac{\lambda_{i+1} - \lambda_i}{2} \left\{ K \left(\frac{\lambda_{i+1} - \lambda_i}{2} \mu + \frac{\lambda_{i+1} + \lambda_i}{2} \right) - 1 \right\}$$

$$\left\{ J_0 \left[a \left(\frac{\lambda_{i+1} - \lambda_i}{2} \mu + \frac{\lambda_{i+1} + \lambda_i}{2} \right) \right] - J_0 \left[2a \left(\frac{\lambda_{i+1} - \lambda_i}{2} \mu + \frac{\lambda_{i+1} + \lambda_i}{2} \right) \right] \right\} \qquad (24)$$

Expressions (23) and (24) were combined and programmed.

DESCRIPTION OF THE PROGRAM

Program Wenner was designed to compute theoretical curves for a Wenner array and match these to field data by an iterative technique.

The apparent resistivity data obtained in the field are used as a first guess at the true resistivities. The surface spacings are used as a first approximation to the layer distribution. With this given layer distribution and the above apparent resistivities, a model curve is computed, compared to the field data, and the resultant error computed.

In subsequent iterations a given resistivity increment is added to or subtracted from each individual layer and the resultant error between field data and model curve compared to the one from the previous model. The change is only accepted if the error is less than the former one. The incremental resistivity changes are initiated at the top layer and proceed to deeper layers. As the iterations progress, small increments are used to adjust the individual resistivity layers of the model. The final best fit for the given layer distribution is then printed out with the final error.

The next step in the curve-matching process is now initiated by the interpreter. Some of the layers can be lumped (or subdivided) to give a simpler layer distribution. This new layer distribution is then put back into the program together with the final computed resistivities and the original field data. The final error output needs then to be compared by the interpreter to that one from the previous layered model. The resistivity of the surface layer must also be chosen by the interpreter from the plotted apparent resistivity data.

BEST DOCUMENT AVAILABLE

TESTING THE PROGRAM

In order to test the program two three-layer model curves were computed with gradually increasing surface spacings.

Model A

Resistivity	Layer thickness
100	20
10	40
100	∞

Model B

Resistivity	Layer thickness
10	20
100	40
10	∞

These models with the resulting outputs from Option B (see app.) are shown on figures 4 and 5 for various increments of resistivity. It becomes, of course, obvious that overadjustment of a particular layer will have to result in erroneous resistivities for adjacent layers. The program will, however, for the three-layer case with known layer thicknesses generate the exact resistivities of the particular layer if the spacing has been taken out far enough. Other cases remain to be tested more thoroughly.

Upon visual inspection of figures 4 and 5 one notices that the three-layer distribution is still apparent in the data. Assuming that the thickness of the middle layer is unknown, various combinations of the central layers are tested for the final error output using Option C.

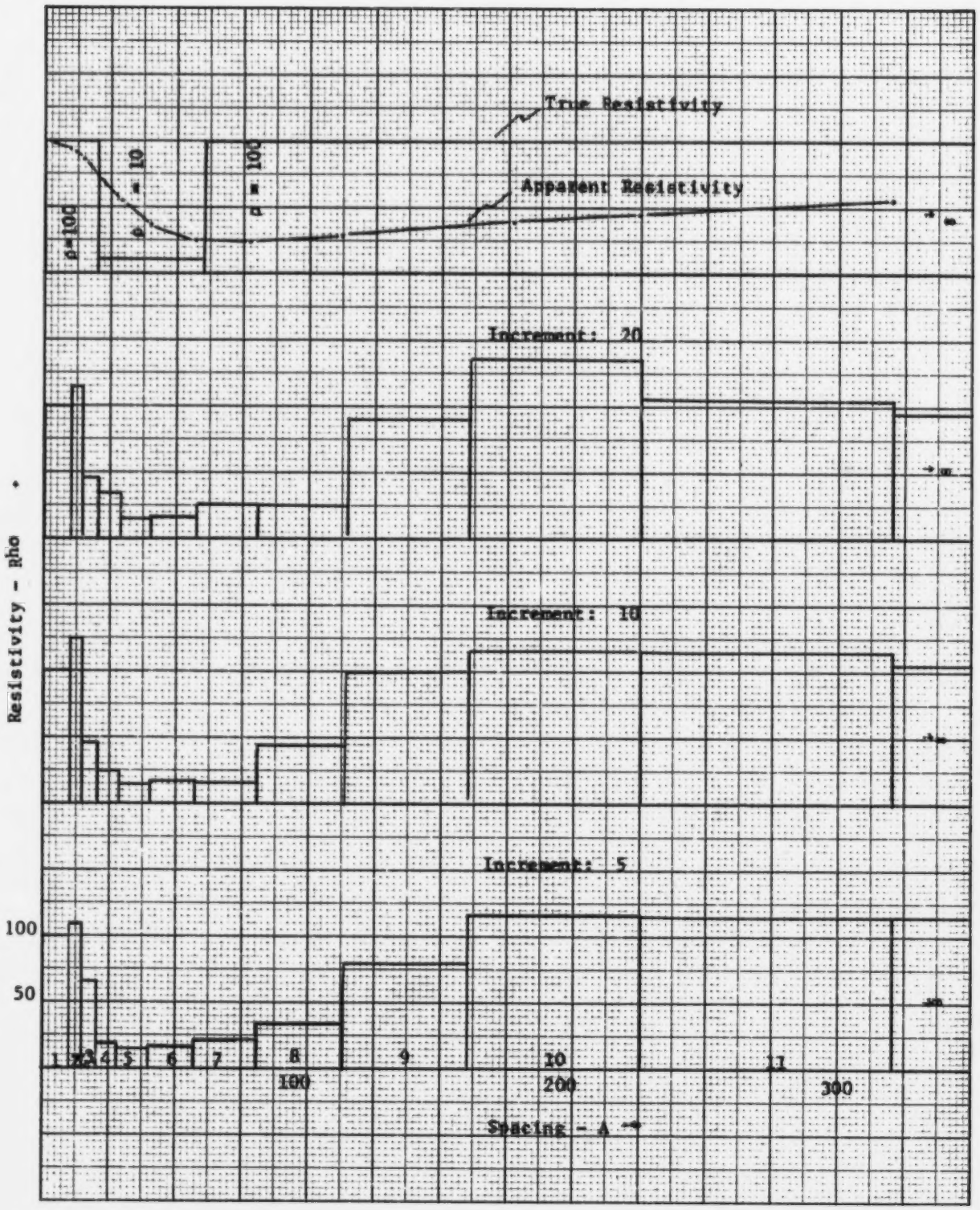

Figure 4.—Three-layer model using surface spacing for layer thickness approximation at various incremental units of resistivity (Model A, Option B).

BEST DOCUMENT AVAILABLE

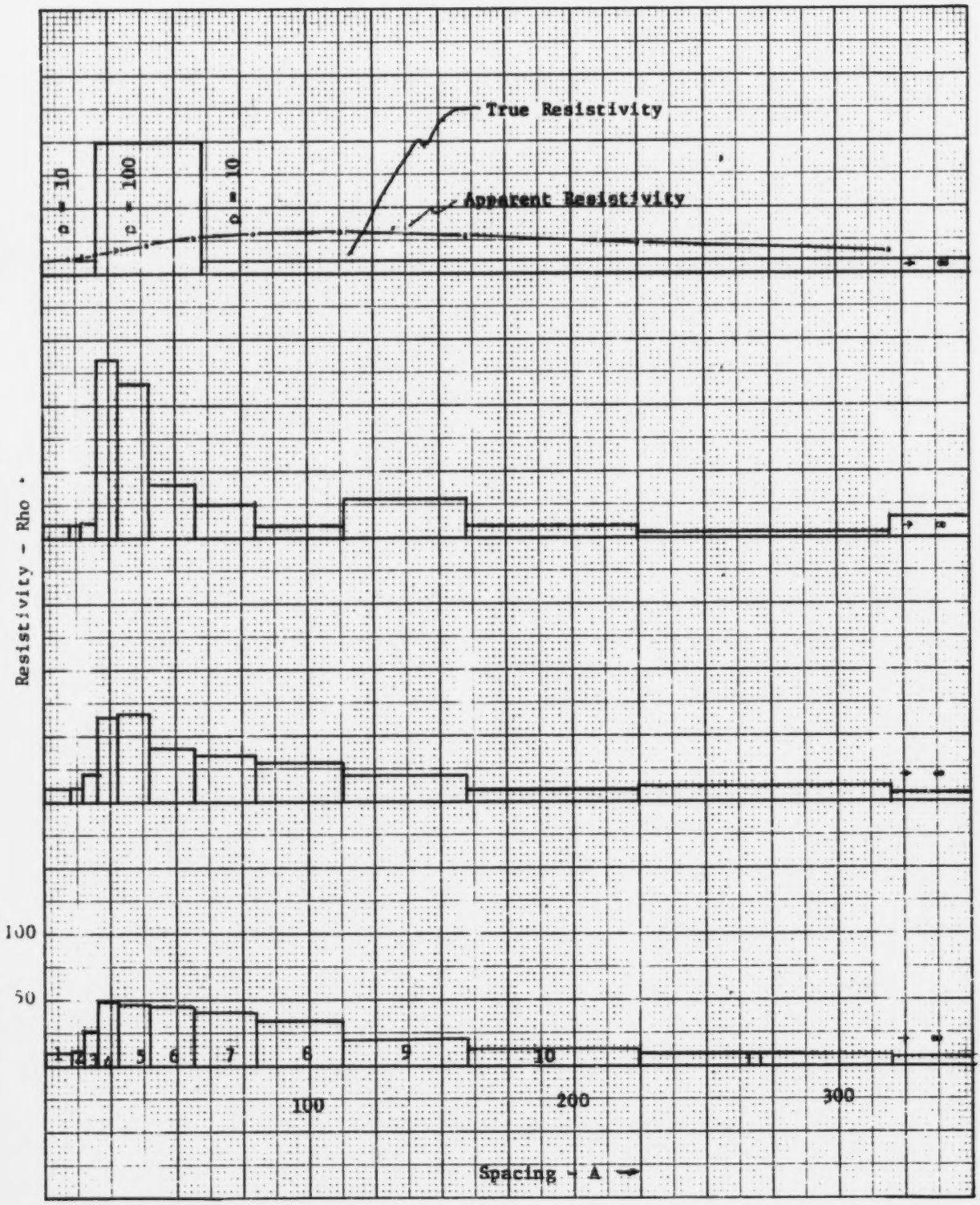

Figure 5.—Three-layer model using surface spacing for layer thickness approximation at various incremental units of resistivity (Model B, Option B).

BEST DOCUMENT AVAILABLE

The tests were conducted as follows (using the output from Option B):

Model A

Test	RHO in	Layers	RHO out	Error
1	100	20(1, 2, 3)	100	0.75E-03
	15	93(4, 5, 6, 7, 8)	18	
	110	∞	151	
2	100	20(1, 2, 3)	100	.32E-03
	15	60(4, 5, 6, 7)	15	
	110	∞	97	
3	100	20(1, 2, 3)	100	.20E-04
	15	37(4, 5, 6)	10	
	110	∞	90	
4	100	20(1, 2, 3)	100	.17E-03
	15	20(4, 5)	5	
	110	∞	102	
5	100	20 } true	100	.19E-06
	15	40 } distribu-	10	
	110	∞ } tion	100.1	

Model B

Test	RHO in	Layers	RHO out	Error
1	10	20(1, 2, 3)	10	0.51E-03
	25	93(4, 5, 6, 7, 8)	57	
	8	∞	6	
2	10	20(1, 2, 3)	10	.10E-03
	25	60(4, 5, 6, 7)	73	
	8	∞	9	
3	10	20(1, 2, 3)	10	.15E-03
	25	37(4, 5, 6)	95	
	8	∞	12	
4	10	20(1, 2, 3)	10	.14E-02
	25	20(4, 5)	125	
	8	∞	18	
5	10	20 } true	10	.75E-05
	25	40 } distribu-	98	
	8	∞ } tion	10.5	

The tests show that for the three-layer case the correct result can be obtained by gradually adjusting the layer thicknesses and comparison of the final error. Incremental resistivity changes of 5 and 2 were used for tests 1 through 4, and 0.5 and 0.1 for test 5. Model B, test 2, shows a smaller error than the corresponding one for test 3. This discrepancy usually disappears when using smaller resistivity increments. It is of prime importance to use the same starting resistivities and identical resistivity increments for each of the tests (1 through 4) when comparing final errors. Test 5 was primarily included to show that, given the correct layering, the program will give exact resistivities.

An example for a four-layer model has also been included (see page 15). The resistivity for the half space is seen to be in error. Including larger spacings in the computations might remedy this particular situation.

When matching field data one might well keep in mind that the resolution of the resistivity method is mostly limited to the three- or four-layer case (i.e., two or three layers above an assumed half space).

Additional layering that one can match to field data is, however, mathematically possible within a great degree of accuracy. Figures 4 and 5 should demonstrate this fact adequately.

CONCLUSIONS

The program was developed for the Bureau of Reclamation for shallow layering in geological engineering applications. For best results, one should have conditions that are characterized by a resistivity distribution of two or three layers. In addition, the program should be restricted to applications of horizontally layered, homogeneous, geologic environments.

In cases where a large number of layers is considered, the curve matching tends to lead to slight errors in resistivity where the boundaries are less clearly defined. Overall accuracy can be improved by going to smaller incremental resistivity changes in the iteration process. This, of course, results in longer iteration times and subsequently increased cost. In cases where greater accuracy

Example of Four-Layer Model

```
APPARENT RESISTIVITY-RHØ    SPACING-A
RHØ=    121.00      A=     10.00
RHØ=    138.00      A=     14.00
RHØ=    160.00      A=     20.00
RHØ=    182.00      A=     28.00
RHØ=    194.00      A=     40.00
RHØ=    188.00      A=     57.00
RHØ=    157.00      A=     80.00
RHØ=    106.00      A=    113.00
RHØ=     54.00      A=    160.00
RHØ=     21.00      A=    226.00
RHØ=     10.00      A=    320.00
RHØ=     14.00      A=    639.00
RHØ=     20.00      A=    900.00
RHØ=     28.00      A=   1280.00
RHØ=     44.00      A=   1810.00
 ERRØR= .170550E-01
 ERRØR= .117776E-01
 ERRØR= .851082E-02
 ERRØR= .630057E-02
 ERRØR= .506523E-02
 ERRØR= .415483E-02
 ERRØR= .339325E-02
 ERRØR= .250958E-02
 ERRØR= .203821E-02
 ERRØR= .185525E-02
 ERRØR= .185525E-02
 RESISTIVITY INCREMENT=   5.00
 ERRØR= .120032E-02
 ERRØR= .112528E-02
 ERRØR= .111490E-02
 ERRØR= .111490E-02
 RESISTIVITY INCREMENT=   1.00
 ERRØR= .920221E-03
 ERRØR= .769854E-03
 ERRØR= .743516E-03
 ERRØR= .722185E-03
 ERRØR= .704102E-03
 ERRØR= .688210E-03
 ERRØR= .674404E-03
 ERRØR= .647761E-03
 ERRØR= .620387E-03
 ERRØR= .596396E-03
 ERRØR= .575989E-03
 ERRØR= .556283E-03
 ERRØR= .537701E-03
 ERRØR= .520200E-03
 ERRØR= .503734E-03
 ERRØR= .488244E-03
 ERRØR= .473708E-03
RESISTIVITY=    100.00    LAYER THICKNESS=     10.00
RESISTIVITY=    298.00    LAYER THICKNESS=     50.00
RESISTIVITY=      2.00    LAYER THICKNESS=     60.00
RESISTIVITY=     52.00    LAYER THICKNESS=      0.
 STØP
```

Four-layer Model:

RHO	Layer thickness
100	10
300	50
1	60
300	∞

BEST DOCUMENT AVAILABLE

is desired, the interpreter has the option of resubmitting adjusted models of an earlier interpretation. Final accuracy, hence, is compromised to reduce computer time and cost. It should, furthermore, be stressed that the field conditions also give rise to errors that generally exceed those resulting from the curve matching technique utilized in this report.

BIBLIOGRAPHY

Abramowitz, M. and I. A. Stegun, eds., *Handbook of Mathematical Functions,* National Bureau of Standards, Applied Mathematics Series, No. 55, pp. 480-91, 1970.

Keller, G. V. and F. C. Frischknecht, *Electrical Methods in Geophysical Prospecting,* 519 pp., Pergamon Press, New York, 1966.

Kunetz, G., *Principles of Direct Current Resistivity Prospecting,* Gebrueder Borntraeger, Berlin, 103 pp., 1966.

Sunde, E. D., *Earth Conduction Effects in Transmission Systems,* 373 pp., D. Van Nostrand Co., Inc., New York, 1949.

Van Nostrand, R. G. and K. L. Cook, "Interpretation of Resistivity Data," U.S. Geological Survey Professional Paper No. 499, 1966.

Ward, S. H., *Mining Geophysics, Vol. II, Theory,* Society of Exploration Geophysics, pp. 87-96, Tulsa, Oklahoma, 1971.

APPENDIX

Program Parameters

The program has three options.

Option A

This option computes the apparent resistivity for a given layer distribution of known thicknesses and resistivities.

Parameters used:

(a) Match

0 (zero - The curve-matching process is omitted)

(b) XXA, NUMLAY

XXA - First layer at which apparent resistivity is to be computed

NUMLAY - Number of layers above half-space

(c) R(L) - Resistivities (for N layers, one needs $N + 1$ resistivities)

(d) H(L) - Layer thicknesses

The output is printed as apparent resistivity - RHO and spacing - A.

Option B

This option accepts apparent resistivities and spacing intervals (for Wenner arrays only), assumes a layer distribution equivalent to surface spacings, and iterates a best fit to the field data. This option is intended as a first guess in the interpretation of field data.

Parameters used:

(a) Match

1 (One - Initiate curve-matching process)

(b) IGUESS

1 (One - Use spacings for layer thicknesses)

(c) J, MAXIT, RHO1, INCMAX

J - Number of input data points (J apparent resistivities for J surface spacings)

MAXIT - Maximum number of iterations - Parameter used to limit cost; the final error between field data and matched curve is printed out at the end of each iteration

RH01 - Resistivity of the first layer - This resistivity must be picked by the interpreter from the plotted field data

INCMAX - Maximum number of increments used for the iterations - The program will generate a final best-fit curve for each given increment and go on to the next one. At the beginning of subsequent increments a message will be printed out. After exhausting all given increments, the program will abort after a final best-fit curve

(d) RESINC(M) - Values of resistivity increments must be listed in order of decreasing magnitude

(e) RAW(L) - Apparent resistivity field data to be matched

(f) XA(L) - Array spacing at the surface

The output will give the resistivities associated with the assumed layer distributions (i.e., equivalent to surface spacings). The input apparent resistivities are also relisted for convenience.

Option C

This option gives the interpreter the capability to pick layer thicknesses independent of the spacing intervals. This gives the interpreter the capability for lumping and thus reducing the initial number of layers. This layer reduction, if accompanied by reduction of total error should eventually lead to a good approximation of the real geologic situation.

Parameters used (see also preceding options):

(a) Match

1

(b) IGUESS

0

(c) NUMLAY

(d) J, MAXIT, RH01, INCMAX

(e) RESINC(M)

(f) RAW(L)

(g) H(L) - Layer thicknesses, to be picked by interpreter

(h) R(L) - Resistivities, to be input by the interpreter

(Use maxima and minima from apparent resisitivity plot as first guess if Option B has not been run before; or use final resistivities from Option B output as guide.)

(i) XA(L)

Output will be given as in Option B.

Program Listing

```
      DIMENSION RESINC(5),RAW(15),H(15),%
      R(15),XA(15),RR(15),EXPO1(15,300),EXPO2(15,300),%
      AXLAM1(300),TABP(15,300),TABM(15,300),EXPON(15,30)
      DIMENSION PREDIF(15)
      IIMAX=300
      CALL INPUT(RAW,H,XXA,J,RINC,LMAX,RHO1,R,%
      ERRMAX,MAXIT,XA,MATCH,RAWS0,INCMAX,RESINC,NUMLAY)
      CALL PARAM1(NUMLAY,H,XA,MATCH,DELRL,LMAX,XXA,R,RHO1)
      CALL TABLE(XA,EXPO1,EXPO2,TABP,TABM,AXLAM1,LMAX,DELRL,%
      NUMLAY,H,EXPON,IIMAX)
      IF(MATCH.EQ.0)GO TO 1
      GO TO 4
    1 CALL KERNEL(R,H,NUMLAY,IMAX,EXPON)
      CALL POT(RHO1,XA,RR,LMAX,IMAX,R,NUMLAY,EXPO1,EXPO2,%
      TABP,TABM,AXLAM1)
      GO TO 2
    4 CONTINUE
      M=1
      RINC=RESINC(1)
      II=1
      N=J+1
      NL=NUMLAY+1
    3 CONTINUE
      IABORT=0
    7 CONTINUE
      CALL ITRATE(RINC,J,MATCH,ERRMAX,II,RAWS0,R,H,NUMLAY,%
      RHO1,XA,RR,LMAX,IMAX,EXPO1,EXPO2,TABP,TABM,%
      AXLAM1,PREDIF,RAW,EXPON)
      CALL CHECK(R,NL,RINC,IABORT,II)
      IF(IABORT.EQ.1)GO TO 6
      II=II+1
      IF(II.GT.MAXIT)GO TO 8
 1001 FORMAT(1X,10(1X,F6.0))
      GO TO 7
    6 CONTINUE
      M=M+1
      IF(M.GT.INCMAX)GO TO 8
      RINC=RESINC(M)
      WRITE(6,1000)RINC
 1000 FORMAT(1X,23H RESISTIVITY INCREMENT=,F6.2)
      GO TO 3
    2 CONTINUE
      CALL OUTPUT(R,XA,LMAX,H,MATCH,RR)
      GO TO 5
    8 CONTINUE
      CALL OUTPUT(R,XA,N,H,MATCH,RR)
    5 CONTINUE
      STOP
      SUBROUTINE ITRATE(RINC,J,MATCH,ERRMAX,II,RAWS0,R,%
      H,NUMLAY,RHO1,XA,RR,LMAX,IMAX,EXPO1,EXPO2,%
```


BEST DOCUMENT AVAILABLE

```
      TABP,TABM,AXLAM1,PREDIF,RAW,EXPON)
      DIMENSION R(45),PREDIF(15),ERR(1),H(15),XA(15),%
      RR(15),EXPO1(15,300),EXPO2(15,300),TABP(15,300),%
      TABM(15,300),AXLAM1(300),RAW(15),EXPON(15,30)
      NN=1
      MM=1
      IF(II.GT.1)GO TO 7
      CALL KERNEL(R,H,NUMLAY,IMAX,EXPON)
      CALL POT(RHO1,XA,RR,LMAX,IMAX,R,NUMLAY,EXPO1,EXPO2,%
      TABP,TABM,AXLAM1)
      IF(MATCH.EQ.0)GO TO 6
      CALL ERROR(RAW,RR,J,ER,RAWSQ,NN,II,PREDIF)
      NN=NN+1
      ERR(1)=ER
    7 CONTINUE
      R(MM+1)=R(MM+1)+RINC
 1001 FORMAT(1X,F5.2)
      CALL KERNEL(R,H,NUMLAY,IMAX,EXPON)
      CALL POT(RHO1,XA,RR,LMAX,IMAX,R,NUMLAY,EXPO1,EXPO2,%
      TABP,TABM,AXLAM1)
      CALL ERROR(RAW,RR,J,ER,RAWSQ,NN,II,PREDIF)
      ERPOS=ER
      IF(ERPOS.GE.ERRMAX)GO TO 2
      GO TO 6
    2 IF(ERR(1)-ERPOS)3,3,4
    4 ERR(1)=ERPOS
      GO TO 14
    3 R(MM+1)=R(MM+1)-2.*RINC
      IF(R(MM+1).LT.0.01)GO TO 10
      CALL KERNEL(R,H,NUMLAY,IMAX,EXPON)
      CALL POT(RHO1,XA,RR,LMAX,IMAX,R,NUMLAY,EXPO1,EXPO2,%
      TABP,TABM,AXLAM1)
      CALL ERROR(RAW,RR,J,ER,RAWSQ,NN,II,PREDIF)
      ERNEG=ER
      IF(ERNEG.GE.ERRMAX)GO TO 9
      GO TO 6
    9 IF(ERNEG-ERR(1))15,10,10
   15 ERR(1)=ERNEG
      GO TO 14
   10 R(MM+1)=R(MM+1)+RINC
   14 CONTINUE
 1000 FORMAT(1X,7H ERROR=,E12.6)
      MM=MM+1
      IF(MM.GT.J)GO TO 8
      GO TO 7
    8 CONTINUE
      WRITE(6,1000)ERR(1)
    6 CONTINUE
      RETURN
      SUBROUTINE INPUT(RAW,H,XXA,J,RINC,LMAX,RHO1,R,%
```


BEST DOCUMENT AVAILABLE

```
      ERRMAX,MAXIT,XA,MATCH,PAWSO,INCMAX,RESINC,NUMLAY)
      DIMENSION RAW(15),H(15),XA(15),RESINC(5),R(15)
      WRITE(6,2001)
 2001 FORMAT(1X,24H INPUT: MATCH:YES=1,NO=0)
      READ(5,*)MATCH
      IF(MATCH.EQ.1)GO TO 12
      WRITE(6,2005)
 2005 FORMAT(1X,17H INPUT:XXA,NUMLAY/%
     1X,60H XXA-FIRST SPACING AT WHICH APPARENT RESIS%
TIVITY IS COMPUTED/1X,41H NUMLAY-NUMBER OF LAYERS %
ABOVE HALF-SPACE)
      READ(5,*)XXA,NUMLAY
      NI=NUMLAY+1
      WRITE(6,2006)
 2006 FORMAT(1X,25H INPUT:R(L)-RESISTIVITIES)
      READ(5,*)(R(L),L=1,NI)
      RHO1=R(1)
      WRITE(6,2007)
 2007 FORMAT(1X,29H INPUT:H(L)-LAYER THICKNESSES)
      READ(5,*)(H(L),L=1,NUMLAY)
      GO TO 13
   12 CONTINUE
      WRITE(6,2002)
 2002 FORMAT(1X,13H INPUT:IGUESS/%
     1X,28H YES-USES PROGRAM PARAMETERS/%
     1X,92H NO-ITERATES,STARTING WITH GIVEN RESISTIVITIES %
AND THICKNESSES MODIFIED FROM PREVIOUS OUTPUT)
      READ(5,*)IGUESS
      IF(IGUESS.EQ.0)GO TO 15
      GO TO 16
   15 WRITE(6,2003)
 2003 FORMAT(1X,30H INPUT:NUMLAY=NUMBER OF LAYERS)
      READ(5,*)NUMLAY
   16 WRITE(6,2004)
 2004 FORMAT(1X,26H INPUT:J,MAXIT,RHO1,INCMAX/%
     1X,24H J-NUMBER OF DATA POINTS/%
     1X,35H MAXIT-MAXIMUM NUMBER OF ITERATIONS/%
     1X,32H RHO1-RESISTIVITY OF FIRST LAYER/%
     1X,48H INCMAX-MAXIMUM NUMBER OF RESISTIVITY INCREMENTS)
      READ(5,*)J,MAXIT,RHO1,INCMAX
      WRITE(6,2010)
 2010 FORMAT(1X,112H INPUT:RESINC(M)-VALUES OF RESISTIVITY %
INCREMENTS FOR ITERATION:INTERVALS MUST BE LISTED %
DECREASING IN MAGNITUDE)
      READ(5,*)(RESINC(M),M=1,INCMAX)
      PAWS0=0.0
      ERRMAX=1.0E-07
      N=J+1
      WRITE(6,2008)
 2008 FORMAT(1X,50H INPUT:RAW(L)-APPARENT RESISTIVITIES %
```


BEST DOCUMENT AVAILABLE

```
TO BE MATCHED)
      READ(5,*)(RAW(L),L=1,J)
      DO 11 L=1,J
      XMULT=RAW(L)*RAW(L)
   11 RAWSQ=RAWSQ+XMULT
      IF(IGUESS.EQ.1)GO TO 1
      NL=NUMLAY+1
      WRITE(6,2007)
      READ(5,*)(R(L),L=1,NUMLAY)
      WRITE(6,2006)
      READ(5,*)(R(L),L=1,NL)
    1 WRITE(6,2009)
 2009 FORMAT(1X,28H INPUT:XA(L)-SURFACE SPACING)
      READ(5,*)(XA(L),L=1,J)
      LMAX=J
      IF(IGUESS.EQ.0)GO TO 10
      NUMLAY=J
      H(1)=XA(1)
      DO 8 L=2,NUMLAY
      H(L)=XA(L)-XA(L-1)
    8 CONTINUE
      R(1)=RHO1
      DO 14 L=1,J
   14 R(L+1)=RAW(L)
   10 CONTINUE
 1003 FORMAT(5H RHO=,F9.2,3X,3H A=,F9.2)
 1004 FORMAT(/37H APPARENT RESISTIVITY-RHO   SPACING-A)
      WRITE(6,1004)
      DO 6 L=1,J
    6 WRITE(6,1003)RAW(L),XA(L)
   13 RETURN
      SUBROUTINE PARAM1(NUMLAY,H,XA,MATCH,DELRL,LMAX,XXA,R,%
      RHO1)
      DIMENSION H(15),XA(15),R(15)
      SUMH=0.
      DO 4 L=1,NUMLAY
    4 SUMH=SUMH+H(L)
      XB=7.*SUMH
      DELRL=.15/XB
      IF(MATCH.EQ.1)GO TO 3
      RHO1=R(1)
      LL=0
      XA(1)=XXA
    5 CONTINUE
      LL=LL+1
      XA(LL+1)=XA(LL)*1.414
      IF(XA(LL)-XB)2,2,3
    2 LMAX=LL
      IF(LL.GE.15)GO TO 3
      GO TO 5
```


BEST DOCUMENT AVAILABLE

```
    3 CONTINUE
      RETURN
      SUBROUTINE KERNEL(R,H,J,IMAX,EXPON)
      DIMENSION R(15),H(15),EXPON(15,50)
      N=J+1
      DO 21 IL=11,30
      ILL=10*IL
      U=(R(J)-R(N))/(R(J)+R(N))
      DO 10 L=1,J
      IP=N-L
      C2=U*EXPON(IP,IL)
      RK=(1.-C2)/(1.+C2)
      IPP=IP-1
      C1=R(IP)*RK
      U=(R(IPP)-C1)/(R(IPP)+C1)
   10 CONTINUE
      EPS=1.0E-05
      IF(ABS(RK-1.).LT.EPS)GO TO 22
   21 IMAX=ILL-1
   22 CONTINUE
      IF(IMAX.GE.290)GO TO 23
      GO TO 24
   23 WRITE(6,3001)
 3001 FORMAT(1X,38H ERROR:PROGRAM PARAMETER EXCEEDED-IMAX)
   24 CONTINUE
      RETURN
      SUBROUTINE POT(RHO1,XA,RR,LMAX,IMAX,R,NUMLAY,EXPO1,%
      EXPO2,TABP,TABM,AXLAM1)
      DIMENSION XA(15),RR(15),PHI(15),R(15)
      DIMENSION EXPO1(15,300),EXPO2(15,300)
      CALL GAUSS(IMAX,LMAX,PHI,EXPO1,EXPO2,TABP,TABM,AXLAM1,%
      R,NUMLAY)
      DO 40 L=1,LMAX
      TWOXA=2.*XA(L)
      RR(L)=(1.+TWOXA*PHI(L))*RHO1
   40 CONTINUE
      RETURN
      SUBROUTINE OUTPUT(R,XA,LMAX,H,MATCH,RR)
      DIMENSION XA(15),R(15),H(15),RR(15)
      IF(MATCH.EQ.0)GO TO 2
      GO TO 4
    2 WRITE(6,5001)
 5001 FORMAT(1X,37H APPARENT RESISTIVITY=RHO; SPACING=A;)
      DO 3 L=1,LMAX
      WRITE(6,5002)RR(L),XA(L)
    3 CONTINUE
      GO TO 5
 5002 FORMAT(1X,5H RHO=,F10.2,3X,3H A=,F10.2)
    4 CONTINUE
      DO 1 L=1,LMAX
```


BEST DOCUMENT AVAILABLE

```
 1003 FORMAT(1X,12HRESISTIVITY=,F9.2,3X,16HLAYER %
THICKNESS=,F9.2)
      WRITE(6,1003)R(L),H(L)
    1 CONTINUE
    5 CONTINUE
      RETURN
      SUBROUTINE BESSEL(ARG,BBJ0)
      DIMENSION A(9),B(6),C(6)
      A(1)=-2.2499997
      A(2)= 1.2656208
      A(3)=-.3163866
      A(4)= .0444479
      A(5)=-.0039444
      B(1)=-.00000077
      B(2)=-.0055274
      B(3)=-.00009512
      B(4)= .00137237
      B(5)=-.00072805
      C(1)=-.04166397
      C(2)=-.00003954
      C(3)= .00262573
      C(4)=-.00054125
      C(5)=-.00029333
      ARG=ABS(ARG)
      IF(ARG-1.5E-03)1,1,2
    1 VALUE=1.
      GO TO 5
    2 IF(ARG-3.0)3,3,4
    3 X=ARG*ARG/9.0
      P=.00021
      DO 10 I=2,6
      N1=7-I
   10 P=P*X+A(N1)
      VALUE=P*X+1.0
      GO TO 5
    4 T=3.0/ARG
      F0=.00014476
      T0=.00013558
      DO 20 I=2,6
      N1=7-I
      F0=F0*T+B(N1)
   20 T0=T0*T+C(N1)
      F0=F0*T+.79788456
      T0=T0*T-.78539816+ARG
      VALUE=1.0/SQRT(ARG)*F0*COS(T0)
    5 BBJ0=VALUE
      RETURN
      SUBROUTINE CHECK(R,N,RINC,IADORT,II)
      DIMENSION R(15),PREVR(15)
      IF(II.GT.1)GO TO 6
```


BEST DOCUMENT AVAILABLE

```
      DO 5 I=1,N
    5 PREVR(I)=0.0
    6 CONTINUE
      SUM=0.0
      DO 1 I=1,N
      DIFF=R(I)-PREVR(I)
      ADIFF=ABS(DIFF)
    1 SUM=SUM+ADIFF
      IF(SUM.LT.RINC)GO TO 2
      GO TO 3
    2 IABORT=1
    3 DO 4 I=1,N
    4 PREVR(I)=R(I)
      RETURN
      SUBROUTINE ERROR(RAW,RR,J,ER,RAWSQ,NN,II,PREDIF)
      DIMENSION RAW(15),RR(15),PREDIF(15),DIFRA(15)
      DIMENSION SUM(1)
      IF(NN.GT.1)GO TO 11
      DO 12 I=1,J
   12 PREDIF(I)=1.0E+08
   11 CONTINUE
      DO 8 I=1,J
      DELRA=RAW(I)-RR(I)
      DIFRA(I)=ABS(DELRA)
      IF(DIFRA(I).LE.1.0)GO TO 8
      IF(DIFRA(I).LE.PREDIF(I))GO TO 8
      GO TO 7
    8 CONTINUE
      DO 9 I=1,J
    9 PREDIF(I)=DIFRA(I)
      SUM1=RAWSQ
      SUM2=0.0
      SUM3=0.0
      DO 2 I=1,J
      FCT1=RAW(I)
      FCT2=RR(I)
      SUM3=SUM3+FCT1*FCT2
      FFCT2=FCT2*FCT2
    2 SUM2=SUM2+FFCT2
      SUM(1)=0.5-SUM3/(SUM1+SUM2)
    7 CONTINUE
      ER=SUM(1)
      RETURN
      SUBROUTINE GAUSS(IMAX,LMAX,PHI,EXPO1,EXPO2,TABP,TABM,%
      AXLAM1,R,NUMLAY)
      DIMENSION PHI(15),AXLAM1(300),EXPO1(15,300),%
      EXPO2(15,300),TABP(15,300),TABM(15,300)
      DIMENSION R(15)
      N=NUMLAY+1
      DO 3 L=1,LMAX
```

BEST DOCUMENT AVAILABLE

```
  3 PHI(L)=0.0
    DO 1 I=1,IMAX
    CALL KERN2(R,NUMLAY,EXPO1,EXPO2,I,XKER1,XKER2)
    PHIM=(XKER2-1.)*AXLAM1(I)
    PHIP=(XKER1-1.)*AXLAM1(I)
    DO 2 L=1,LMAX
    PHI(L)=PHI(L)+PHIM*TABM(L,I)+PHIP*TABP(L,I)
  2 CONTINUE
  1 CONTINUE
    RETURN
    SUBROUTINE KERN2(R,JJ,EXPO1,EXPO2,I,RK1,RK2)
    DIMENSION R(15),EXPO1(15,300),EXPO2(15,300)
    N=JJ+1
    U=(R(JJ)-R(JJ+1))/(R(JJ)+R(JJ+1))
    U1=U
    U2=U
    DO 10 L=1,JJ
    IP=JJ-L
    C21=U1*EXPO1(IP,I)
    C22=U2*EXPO2(IP,I)
    RK1=(1.-C21)/(1.+C21)
    RK2=(1.-C22)/(1.+C22)
    IPP=IP-1
    C11=R(IP)*RK1
    C12=R(IP)*RK2
    U1=(R(IPP)-C11)/(R(IPP)+C11)
    U2=(R(IPP)-C12)/(R(IPP)+C12)
 10 CONTINUE
    RETURN
    SUBROUTINE TABLE(XA,EXPO1,EXPO2,TABP,TABM,AXLAM1,LMAX,%
    DELRL,J,H,EXPON,IIMAX)
    DIMENSION TABP(15,300),TABM(15,300),XA(15),RL(300),%
    AXLAM1(300),H(15),EXPON(15,30),B1(300),B2(300)
    DIMENSION EXPO1(15,300),EXPO2(15,300)
    N=J+1
    RL(1)=0.01*DELRL
    IK=IIMAX-1
    DO 4 I=1,IK
  4 RL(I+1)=(RL(I)+DELRL)*1.02
    DO 5 IL=11,30
    ILL=10*IL
    TWORL=-2.*RL(ILL)
    DO 3 K=1,J
    IP=N-K
    EX=TWORL*H(IP)
  3 EXPON(IP,IL)=EXP(EX)
  5 CONTINUE
    DO 1 I=1,IK
    XLAM1=(RL(I+1)-RL(I))*.5
    AXLAM1(I)=XLAM1
```


BEST DOCUMENT AVAILABLE

```
      XLAM2=(RL(I+1)+RL(I))*.5
      A1=XLAM1*0.577350269189626
      B1(I)=A1+XLAM2
      B2(I)=-A1+XLAM2
      TWORL1=-2.*B1(I)
      TWORL2=-2.*B2(I)
      DO 6 KK=1,J
      IPP=N-KK
      EX1=TWORL1*H(IPP)
      EX2=TWORL2*H(IPP)
      EXPO1(IPP,I)=EXP(EX1)
    6 EXPO2(IPP,I)=EXP(EX2)
      DO 2 L=1,LMAX
      ARGA1=XA(L)*B1(I)
      ARG2A1=ARGA1+ARGA1
      ARGA2=XA(L)*B2(I)
      ARG2A2=ARGA2+ARGA2
      CALL BESSEL(ARGA1,BA1)
      CALL BESSEL(ARG2A1,B2A1)
      CALL BESSEL(ARGA2,BA2)
      CALL BESSEL(ARG2A2,B2A2)
      TABP(L,I)=BA1-B2A1
      TABM(L,I)=BA2-B2A2
    2 CONTINUE
    1 CONTINUE
      RETURN
      END
```

Example of Option A

```
PORT: 83
CENTEL: RB


TERMINAL 1044    06/12/73    06:57:34
LOGON:  GPS UBT003,      023304
ADMSPS A EDIT/L INFORM 6/06/73
!MENNEF
 INPUT: MATCH;YES=1,NO=0
0
 INPUT:XXA,NUMLAY
 XXA-FIRST SPACING AT WHICH APPARENT RESISTIVITY IS COMPUTED
 NUMLAY-NUMBER OF LAYERS ABOVE HALF-SPACE
10,2
 INPUT:R(L)-RESISTIVITIES
100,10,100
 INPUT:H(L)-LAYER THICKNESSES
20,40
 APPARENT RESISTIVITY=RHO; SPACING=A:
 RHO=      94.47     A=      10.00
 RHO=      87.16     A=      14.14
 RHO=      73.97     A=      19.99
 RHO=      55.21     A=      28.27
 RHO=      36.71     A=      39.98
 RHO=      25.50     A=      56.53
 RHO=      23.87     A=      79.93
 RHO=      28.65     A=     113.09
 RHO=      36.34     A=     159.81
 RHO=      45.41     A=     225.97
 RHO=      55.24     A=     319.52
 STOP
SRU'S:14.9
```

Example of Option B

```
!SCRIP
 INPUT: MATCH;YES=1,NO=0
1
 INPUT:GUESS
 YES-USES PROGRAM PARAMETERS
 NO-ITERATES,STARTING WITH GIVEN RESISTIVITIES AND THICKNESSES MODIFIED
FROM PREVIOUS OUTPUT
1
 INPUT:J,MAXIT,RHO1,INCMAX
 J-NUMBER OF DATA POINTS
 MAXIT-MAXIMUM NUMBER OF ITERATIONS
 RHO1-RESISTIVITY OF FIRST LAYER
 INCMAX-MAXIMUM NUMBER OF RESISTIVITY INCREMENTS
11,20,100,1
 INPUT:RESINC(M)-VALUES OF RESISTIVITY INCREMENTS FOR ITERATION;INTERVAL
S MUST BE LISTED DECREASING IN MAGNITUDE
20
 INPUT:RAW(L)-APPARENT RESISTIVITIES TO BE MATCHED
94.47,87.16,73.57,55.21,36.71,25.5,23.87,28.65,36.34,45.41,55.24
 INPUT:XA(L)-SURFACE SPACING
10.,14.14,19.99,28.27,39.98,56.53,79.93,113.02,159.81,225.97,319.52

APPARENT RESISTIVITY-RHO   SPACING-A
RHO=     94.47     A=     10.00
RHO=     87.16     A=     14.14
RHO=     73.57     A=     19.99
RHO=     55.21     A=     28.27
RHO=     36.71     A=     39.98
RHO=     25.50     A=     56.53
RHO=     23.87     A=     79.93
RHO=     28.65     A=    113.02
RHO=     36.34     A=    159.81
RHO=     45.41     A=    225.97
RHO=     55.24     A=    319.52
 ERROR= .619823E-02
 ERROR= .384731E-02
 ERROR= .101160E-02
 ERROR= .787079E-03
 ERROR= .323825E-03
 ERROR= .323825E-03
RESISTIVITY=    100.00   LAYER THICKNESS=     10.00
RESISTIVITY=    114.47   LAYER THICKNESS=      4.14
RESISTIVITY=     47.16   LAYER THICKNESS=      5.85
RESISTIVITY=     33.87   LAYER THICKNESS=      8.28
RESISTIVITY=     15.21   LAYER THICKNESS=     11.71
RESISTIVITY=     16.71   LAYER THICKNESS=     16.55
RESISTIVITY=     25.50   LAYER THICKNESS=     23.40
RESISTIVITY=     23.87   LAYER THICKNESS=     33.09
RESISTIVITY=     28.65   LAYER THICKNESS=     46.79
RESISTIVITY=    136.34   LAYER THICKNESS=     66.16
RESISTIVITY=    105.41   LAYER THICKNESS=     93.55
RESISTIVITY=     95.24   LAYER THICKNESS=      0.
 STOP
SRU'S:141.5
```


BEST DOCUMENT AVAILABLE

Example of Option C

```
!WENNER
 INPUT: MATCH;YES=1,NO=0
1
 INPUT:IGUESS
 YES-USES PROGRAM PARAMETERS
 NO-ITERATES,STARTING WITH GIVEN RESISTIVITIES AND THICKNESSES MODIFIED
FROM PREVIOUS OUTPUT
0
 INPUT:NUMLAY=NUMBER OF LAYERS
2
 INPUT:J,MAXIT,RHO1,INCMAX
 J-NUMBER OF DATA POINTS
 MAXIT-MAXIMUM NUMBER OF ITERATIONS
 RHO1-RESISTIVITY OF FIRST LAYER
 INCMAX-MAXIMUM NUMBER OF RESISTIVITY INCREMENTS
11,30,10,3
 INPUT:RESINC(M)-VALUES OF RESISTIVITY INCREMENTS FOR ITERATION;INTERVAL
S MUST BE LISTED DECREASING IN MAGNITUDE
10,5,1
 INPUT:RAW(L)-APPARENT RESISTIVITIES TO BE MATCHED
10.69,11.66,13.58,16.73,20.96,25.51,29.11,30.26,28.08,23.05,17.38
 INPUT:H(L)-LAYER THICKNESSES
20,40
 INPUT:R(L)-RESISTIVITIES
10,30,15
 INPUT:XA(L)-SURFACE SPACING
10.,14.14,19.99,28.27,39.98,56.53,79.93,113.02,159.81,225.97,319.52

APPARENT RESISTIVITY-RHO   SPACING-A
RHO=     10.69     A=     10.00
RHO=     11.66     A=     14.14
RHO=     13.58     A=     19.99
RHO=     16.73     A=     28.27
RHO=     20.96     A=     39.98
RHO=     25.51     A=     56.53
RHO=     29.11     A=     79.93
RHO=     30.26     A=    113.02
RHO=     28.08     A=    159.81
RHO=     23.05     A=    225.97
RHO=     17.38     A=    319.52
 ERROR= .944601E-02
 ERROR= .739299E-02
 ERROR= .398343E-02
 ERROR= .157955E-02
 ERROR= .785939E-03
 ERROR= .785939E-03
 RESISTIVITY INCREMENT=     5.
 ERROR= .785939E-03
 RESISTIVITY INCREMENT=     1.
 ERROR= .570938E-03
 ERROR= .498466E-03
 ERROR= .431597E-03
```


BEST DOCUMENT AVAILABLE

```
 ERROR= .377037E-03
 ERROR= .334412E-03
 ERROR= .303373E-03
 ERROR= .258692E-03
 ERROR= .208721E-03
 ERROR= .170246E-03
 ERROR= .142947E-03
 ERROR= .126533E-03
 ERROR= .110991E-03
 ERROR= .747517E-04
 ERROR= .493601E-04
 ERROR= .345111E-04
 ERROR= .299439E-04
 ERROR= .299439E-04
RESISTIVITY=     10.00    LAYER THICKNESS=     20.00
RESISTIVITY=     96.00    LAYER THICKNESS=     40.00
RESISTIVITY=     11.00    LAYER THICKNESS=      0.
 STOP
SRU'S:86.6
```

BEST DOCUMENT AVAILABLE

Example of Delayed Processing

```
!EDIT IN1
↑L
   10       1
   20       1
   30       11,20,100,2
   40       5,2
   50       94.47,87.16,73.87,55.21,36.71,25.5,23.87,28.65,36.34,45.41,55
.24
   60       10.,14.14,19.99,28.27,39.98,56.53,79.93,113.02,159.81,205.97,
319.59
↑G
SRU'S:.6
!EDIT TEST1
↑L
   10       !SWITCH IN:IN1 OUTS:OUT1
   20       !LIMIT USE:600
   30       !USAGE,LIMIT
   40       !MATCH
   50       !SWITCH INS:,CLOSE OUTS:,CLOSE
   60       !SAVE OUT1
   70       !USAGE,LIMIT
   80       !OFF
↑G
SRU'S:.4
!JOB,9 TEST1 'GPS UB1003,PROG,023304,AGG1' 0001000012
GPS362   TEST1-PAG/LIES     17600
!OFF
USAGE ON 06/11/73 AT 08:06:55
SRU'S:3.4        ELAPSED TIME: 00:05:07
GOOD BYE.
↑


 T

PORT: 83
CENTER: 88




TERMINAL 1215    06/11/73    08:49:37
LOGIN:  GPS UB1003,      023304
ADR788 A EDIT/L INFILE 6/06/73
!EDIT OUT1
↑L
  INPUT: MATCH:YES=1,NO=0
  INPUT:IGUESS
  YES-USES PROGRAM PARAMETERS
  NO-INITIATES,STARTING WITH GIVEN RESISTIVITIES AND THICKNESSES MODIFIED
 FROM PREVIOUS OUTPUT
  INPUT:J,MAXIT,EPSI,INCMAX
  J-NUMBER OF DATA POINTS
  MAXIT-MAXIMUM NUMBER OF ITERATIONS
  EPSI-RESISTIVITY OF FIRST LAYER
  INCMAX-MAXIMUM NUMBER OF RESISTIVITY INCREMENTS
  INPUT:INCSING(J)-VALUES OF RESISTIVITY INCREMENTS FOR INTERATION:1,2,3,4
```


BEST DOCUMENT AVAILABLE

```
LS MUST BE LISTED DECREASING IN MAGNITUDE
  INPUT:RAW(L)-APPARENT RESISTIVITIES TO BE MATCHED
  INPUT:XA(L)-SURFACE SPACING

 APPARENT RESISTIVITY-RHO   SPACING-A
 RHO=     94.47     A=     10.00
 RHO=     87.16     A=     14.14
 RHO=     73.87     A=     19.99
 RHO=     55.21     A=     28.27
 RHO=     36.71     A=     39.98
 RHO=     25.50     A=     56.53
 RHO=     23.87     A=     79.93
 RHO=     28.65     A=    113.02
 RHO=     36.34     A=    159.81
 RHO=     45.41     A=    225.97
 RHO=     55.24     A=    319.52
  ERROR= .213115E-01
  ERROR= .619823E-02
  ERROR= .384731E-02
  ERROR= .101160E-02
  ERROR= .787079E-03
  ERROR= .323825E-03
  ERROR= .323825E-03
 RESISTIVITY=    100.00    LAYER THICKNESS=     10.00
 RESISTIVITY=    114.47    LAYER THICKNESS=      4.14
 RESISTIVITY=     47.16    LAYER THICKNESS=      5.85
 RESISTIVITY=     33.87    LAYER THICKNESS=      8.28
 RESISTIVITY=     15.21    LAYER THICKNESS=     11.71
 RESISTIVITY=     16.71    LAYER THICKNESS=     16.55
 RESISTIVITY=     25.50    LAYER THICKNESS=     23.40
 RESISTIVITY=     23.87    LAYER THICKNESS=     33.09
 RESISTIVITY=     88.65    LAYER THICKNESS=     46.79
 RESISTIVITY=    136.34    LAYER THICKNESS=     66.16
 RESISTIVITY=    105.41    LAYER THICKNESS=     93.55
 RESISTIVITY=     95.24    LAYER THICKNESS=      0.
  STOP
↑C
SRU'S:.7
!EDIT ACC1
↑L
 !SWITCH INS:IN1 OUTS:OUT1
 !LIMIT USE:600
 !USAGE,LIMIT
 USE:0      TIME: 00:00:11  LINES:3       GROWTH:0      , 115   ,  0

 !MATCH
 SRU'S:120.5
 !SWITCH INS:,CLOSE OUTS:,CLOSE
 !SAVE OUT1
 CPS354 I OUT1-PRC SAVED
 !USAGE,LIMIT
 USE:49     TIME: 00:04:05  LINES:55      GROWTH:0      , 174   ,  1

 !OFF
 USAGE ON 06/11/73 AT 09:10:22
 SRU'S:121.7     ELAPSED TIME: 00:04:06
↑C
SRU'S:.5
```


☆ U.S. GOVERNMENT PRINTING OFFICE: 1981 — 781-479/508 Region No. 8

BEST DOCUMENT AVAILABLE

A free pamphlet is available from the Bureau of Reclamation entitled, "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request to the Bureau of Reclamation, Engineering and Research Center, PO Box 25007, Denver Federal Center, Bldg. 67, Denver, CO 80225, Attn D-922.